NONLINEAR WAVE MECHANICS AND TECHNOLOGIES, WAVE AND OSCILLATORY PHENOMENA ON THE BASIS OF HIGH TECHNOLOGIES

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Preface

This book is devoted to a systematic statement of the principles of nonlinear wave mechanics—a new branch of mechanics—which is a scientific basis for wave technologies, having no analogues in world practice.

New wave and oscillating phenomena and effects, which form the basis of highly intensive wave technologies, are discovered during the development of nonlinear wave mechanics. These wave technologies have applications in numerous industries, i.e., in oil and gas production for the enhancement of oil-and-gas condensate recovery of layers, in the energy sector, in engineering, in process industries such as oil refining and petrochemistry, in the food industry, in ecology, in material science including production of building materials and nanocomposites, in the cosmetics industry, in pharmaceuticals, etc.

The results of the application of wave technologies in most cases cannot be obtained in practice by the methods known at present concerning the quality of the materials and products, the power inputs (a high quality of the products obtained using wave technologies is achieved at a significant reduction of power inputs), and other indicators. The necessity to implement the wave technologies in practice has led to the development of a new area of mechanical engineering, namely, wave engineering.

One of the specific peculiarities of wave mechanics is the fact that the formulations of the mechanical and mathematical problems, to the solution of which wave mechanics is devoted, have arisen directly from the needs of modern practice, namely, from the analysis of typical technologies in many industries, or to intensify substantially and to reduce the power inputs during a technological process, or from the necessity to work out fundamentally new science-intensive technologies, for example, for obtaining materials and products with unique properties, etc.

It should be noted that nonlinear wave phenomena and effects, which were first established theoretically, have been, as a rule, verified many times in experiments not only in vitro, but also in full-scale experiments. They are the basic principles employed while working out the wave machines and apparatus, and implementing highly intensive wave technologies.

Various and rather complicated original mathematical models have been applied to the development of the scientific foundations of nonlinear wave mechanics. The investigation of these models has been carried out not only by means of the most modern numerical methods of computer simulating, but also by using a powerful analytical apparatus of classical methods of nonlinear mechanics (methods of small parameters of Henri Poincaré, asymptotic methods of Nikolay N. Bogolyubov and Nikolay M. Krylov, different variants of the averaging method, stability theory of motion according to Aleksandr M. Lyapunov, etc.), which have been modified for the cases of nonlinear resonances. It should be noted that it is mathematically rigorous analytical methods of nonlinear mechanics that have played a major role in determining wave phenomena and effects. Analytical methods have become the "core," around which the technique of establishment of the wave and oscillating phenomena of nonlinear wave mechanics and understanding of their mechanisms has been generated.

The main results (nonclassical formulations of the problems, methods of investigation, new relationships of wave and oscillating processes in multiphase systems, wave mechanisms of motions and of stabilization, wave and oscillating phenomena and effects), presented in detail in this book, show quite conclusively that a number of wave phenomena and effects can hardly be obtained (even using the most ultimate modern supercomputers) without a successful preliminary analytical procedure of the establishment of the modes of motion. Here, analytics provides a clear understanding of the physics and mechanics of nonlinear wave phenomena. These moments are likely to be taken as a rather natural approach by physicists and engineers delving into complex nonlinear wave and oscillating processes, especially at the conditions of nonlinear resonances. Certainly, in order to successfully solve such complex problems, it is necessary to reveal a certain art while formulating the problems on mechanics, based on the experience of work in the field of nonlinear oscillations and practical observations over oscillating and wave processes.

This book is mainly devoted to the description of the fundamental principles of nonlinear wave mechanics, including the theory of nonlinear oscillations of multiphase systems and wave mechanisms of motion, phenomena and effects, discovered within this theory, that have practical applications (during the development of science-intensive technologies). Significant attention is also paid to the description of the developed typical wave technologies and wave machines and apparatus, and implementing these technologies, that is, to a wave engineering. Several results of practical implementations in different technological sectors and further perspectives of the development of both nonlinear wave mechanics and wave technologies are also stated.

Nonlinear wave mechanics and wave technologies are created, verified in experiments, tested in practice, and in some cases implemented by both the authors of this book themselves and the team under their scientific guidance (their apprentices and colleagues) from the Scientific Center for Nonlinear Wave Mechanics and Technology of the Russian Academy of Sciences, in close contact with different engineering organizations. The main part of the results is published in the books and papers of the collaborators of this team and is protected by patents in Russia and abroad.

A number of sections of this book are written by the authors together with certain collaborators and their colleagues, whose level of participation is indicated in the corresponding sections.

The authors would like to express their deep gratitude to all these collaborators.

Introduction

We focus on the main ideas of nonlinear wave mechanics and wave technologies. We give a brief description of typical scientific problems, wave motions, forces of wave nature, and wave effects; and their role in creating new technologies and machines.

For several decades, the Scientific Center for Nonlinear Wave Mechanics and Technology of the Russian Academy of Sciences, together with organizations of various industries in Russia and abroad (oil and gas production, oil refining, chemistry and petrochemistry, building sector, engineering industry, ecology, food industry, material science including production of building materials, etc.), have been carrying out fundamental research (theoretical and experimental), as well as pilot and industrial experiments to find out the fundamentally new possibilities for the application of wave and oscillating processes in new equipment and technological procedures.

This work has led to the elaboration of scientific basis for so-called nonlinear wave mechanics of multiphase systems (theory of nonlinear oscillations of multiphase systems, which is focused on typical processes of technologies), which is a new branch of the oscillation theory. Meanwhile, the pilot and full-scale experiments, which are currently being implemented in practice, are fulfilled jointly with industry design offices and enterprises.

The main results of both fundamental and applied investigations in this area, that is, the principles of nonlinear wave mechanics of multiphase systems and wave technologies, and the prospects of their applications, are presented here.

I. Formulation of the Problems in Nonlinear Wave Mechanics (Nonlinear Oscillations of Multiphase Systems) and Wave Technologies

The field of nonlinear wave mechanics of multiphase systems considered here (theory of nonlinear oscillations of multiphase systems) refers to a rather wide and currently highly developed branch of mechanics of nonlinear oscillations and waves. It is generally recognized that in fact Russia is a native country for the theory of nonlinear oscillations. In any case, our leading scientists have made a significant contribution to the mechanics of nonlinear oscillations. We owe this, above all, to a number of Russian and Soviet scientists, namely, A. M. Lyapunov, A. N. Krylov, N. M. Krylov, N. N. Bogolubov, L. I. Mandelshtam, and A. A. Andronov and their schools, as well as many other known scientists.

Several Institutes of the Russian Academy of Sciences and other agencies have made a significant contribution to this area. The theory of nonlinear oscillations has been developed to a rather high degree in our country. At present, Russian science is ahead of the foreign world in a number of directions in this area.

Unfortunately, the scope of works is now significantly reduced in Russia, although the world of oscillations and waves is still enormous. Physicists and acousticians are engaged in the field of oscillations; chemists and biologists are beginning to be concerned with it. This book is not of a review character, but is only devoted to the description of the scientific basis for nonlinear wave mechanics and wave technology.

First of all, let us note that the scientific formulation of the problems of nonlinear wave mechanics of hydromechanical (multiphase) systems has arisen from practical needs, on the basis of the analysis of the needs of the oil industry, applied chemistry, the engineering industry, the energy sector, the agricultural sector, building, ecology, material science, the food industry, etc. General technological processes from various industries (for processing the multiphase media) are listed below.

Different types of multiphase media are presented schematically in Figs. 1–3, respectively, which include a mixture of liquids and dispersed elements of gas, and solid inclusions of different densities and sizes, as well as inclusions of other liquids; a porous medium rich in liquid and (or) gas, or in a mixture of liquid with dispersed inclusions; granulated solids of a dissimilar structure. Liquid, skeleton, solid particles, and bubbles are denoted in Fig. 2 by numbers 1, 2, 3, and 4, correspondingly. Particles of free-flowing

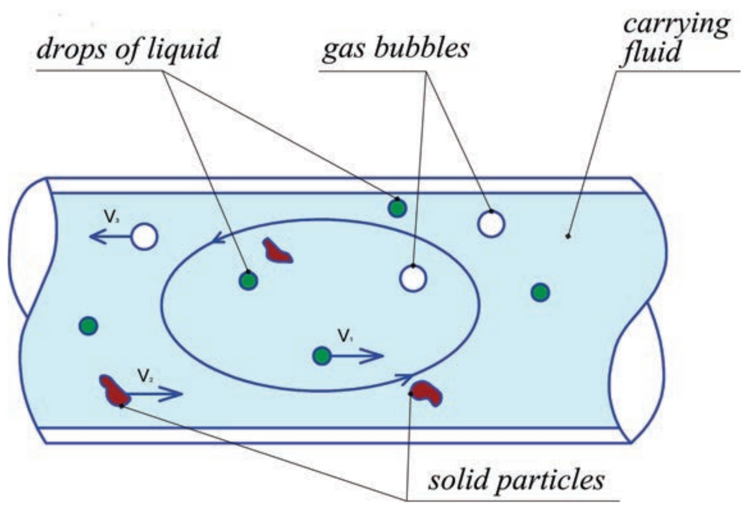

FIG. 1

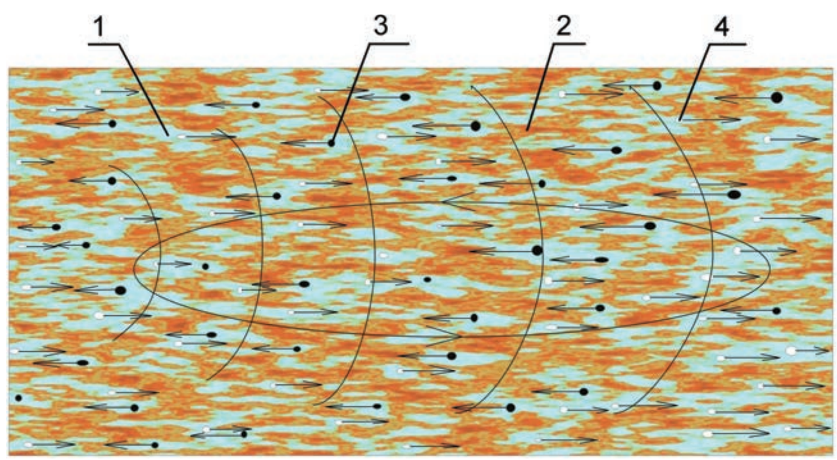

FIG. 2

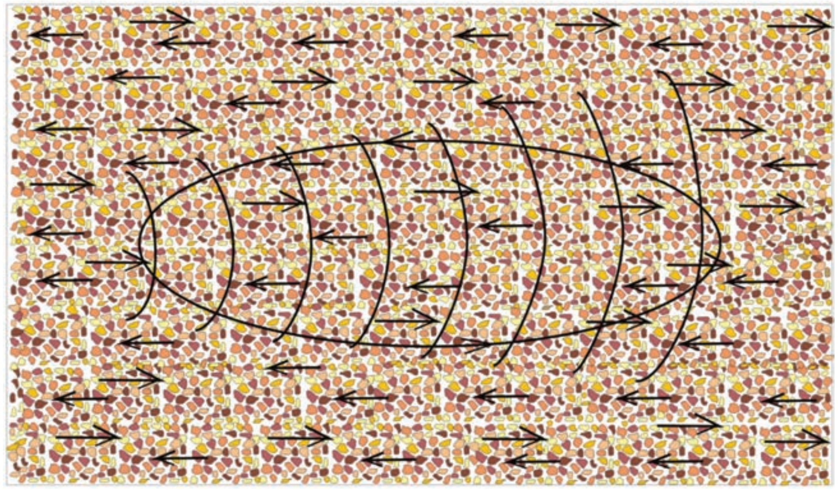

FIG. 3

medium of different sizes and densities are denoted in Fig. 3 by various colors. These are only a few examples.

In general, the multiphase media are suspensions, emulsions, gas suspensions, aerosols, fluids with bubbles of gas (vapor), etc. They are widely represented in different natural and technological processes.

In many reactors and apparatus for oil and gas refinement and chemical technology, and in oil and gas layers, as well as in atomic and heat energy systems, there are mechanical modes of motions or equilibrium states of multiphase media; particularly, the laws of motions or equilibrium of dispersed phases (drops, bubbles, solid particles) relative to the dispersing phase (surrounding and carrying phase) that determine the operating process. Meanwhile, a majority of physicochemical processes—phase transitions, chemical reactions, heat-mass exchange, subdivision or coagulation of particles, and others—are caused by mechanical motions of a multiphase medium. Thus, one of the important elements in creating the technological processes is the definition of the required laws of motion at minimum expenditure of energy, but conserving the maximum efficiency of the process. The generation of such motions can in many cases be implemented most efficiently on the basis of powerful wave or oscillating resonance effects in multiphase systems. The system of mechanical structure, such as a reactor, apparatus, pipeline, or others, with a multiphase medium is referred to as a multiphase system in this book. It is possible to discuss resonance phenomena and effects with respect to such a mechanical system.

The reasonability of the formulation of the problem on wave technology of multiphase systems is first of all due to the fact that the technological processes are, as a rule, “wave” in nature. For example, during the technological process, the motions or the relative equilibrium states (of a dispersed phase) of multiphase media are always either accompanied by the oscillating components, which are quite small, or the internal structure of a medium is able to generate wave phenomena (potentially oscillating) under certain conditions. In addition, the physicochemical transformations or the variations in component concentrations during chemical reactions are often also of a wave or periodic (oscillating) character. In such a generalized sense, wave and oscillating properties are inherent in many natural and technological processes.

Under the conditions of nonlinear resonance interactions, the wave and oscillating motions of the system can significantly influence its main motion or equilibrium state. Therefore, the main aim now is to generate the required controlled motions of the multiphase system or the stabilization of its equilibrium states due to the control of small wave or oscillating processes. The latter can be implemented either actively by means of external periodical influences of a different physical nature (low-frequency or high-frequency vibrating effects, ultrasound, alternating electric or magnetic fields, etc.), or passively by certain structural changes in the apparatus, at which the desired oscillating motions will be implemented without external vibrating effects (for example, self-oscillating systems or a boundary layer passive control). Here, one of the main ideas consists in that it is due to the control (passive or active) of quite small (practically, hardly visible) motions of a wave or oscillating character correspondingly at small energy expenditures under the conditions of nonlinear resonance interaction that the problem on a substantial variation of dynamic characteristics of the multiphase system is formulated; that is, the problem of generation of strong additional motions, not necessarily of an oscillating character (periodical or monotone motions of the medium), relative motions of dispersed phases, generation of stable equilibrium states of dispersed phases, etc.

In order to answer this question more fully, we will outline, though somewhat anticipatingly, some specific aspects of nonlinear oscillations in nature and in technology. They are very versatile—and sometimes paradoxical. For example (as is shown in the sections below), the periodic effects on liquids or multiphase media, and systems of rigid and elastic bodies, can produce various modes of motions such as translatory motions (displacement of liquids, granular media, solid particles, and gas with respect to the fluid), vortex motions, phase mixing, localizations of dispersed phases and their stable retention, and nonlinear waves (shock waves). Therefore, the oscillations produce not only new oscillations, but also different periodic and monotone motions, accelerations and deceleration of motions, stabilization of equilibrium states, and other resonance effects. Such developments are caused by a radical transfer of the energy of wave or oscillating motions to the energy of other modes of mechanical motions and equilibriums under the conditions of strong nonlinear dynamic interactions. “Weak disturbances,” which could almost be neglected, turn out to determine the dynamic process in the multiphase systems under the conditions of nonlinear resonance interactions. Here we consider nonlinear resonances in a a broader meaning than it is universally accepted in the engineering theory of oscillations. There can be many resonances in nonlinear multiphase systems, and the capture regions of them are much wider as compared to common resonances.

It is in this kind of effects that the applications of nonlinear oscillations in technology are attractive. For example, imagine now the application of wave effects in the technological processes, where the weight forces are dominant (gravitational preparation of ore, gravitational segregation while filtering, etc.). The application of powerful resonance wave effects (the forces arising while doing it can exceed by several orders the weight forces and can influence the medium in different directions in space, in contrast to a unidirectional weight force) can lead to either the creation of new technological processes or to a substantial intensification of existing processes. Meanwhile, the oscillations have a strong selective action on the motion of dispersed media, which is especially important, for example, in a fine filtering of fuel, liquids, and in a separation of rare metals of a special value with very similar specific weights. For such processes, there are no efficient technical solutions nowadays.

Wave effects can be successfully applied not only in technological processes, where the moving forces are the weight forces (these processes have been considered only as typical cases, in which the advantage in application the wave and oscillating effects is clearly seen), but also in many other operations in which the oscillations are likely to be not needed. The wave technological processes can be based, for example, on the generation of powerful additional pressures by means of resonance wave effects (multifold amplification of static pressure in a closed volume of a fluid mixture with bubbles under the influence of a small periodical disturbance), or on the control of the motions of fluids and gases in a bounded space or in pipelines by means of the optimal redistribution of energy of the oscillating motions that always accompany the monotone motions of fluids and gases. Where there is movement, there are variations. There are examples of the rational use of oscillating phenomena in nature. It is, for example, a motion of dolphins, or a flight of some birds whose drag decreases due to the oscillating processes. According to some assumptions, the same wave mechanism can occur in the human cardiovascular system (blood flow in blood vessels under the periodic effects caused by the work of the heart).

Unfortunately, despite opportunities of using the wave processes in the multiphase systems in technologies, this area is not developed enough at present. There are teams in Russia and in CIS countries that have made significant progress, both in theory and in applied investigations in the field of scientific basis and certain concrete areas of vibrotechnics and vibration technology. This applies mainly to the usage of vibration machines, as well as to the vibratory displacement and classification of granular media in the building, metallurgy, mining, and some other industries.

As concerns a number of important technological processes, in particular, for the fuel and energy industry, in fact until the early 1970s, there were no basic scientific formulations of the relevant fundamental problems, and there are no relevant major application results. Exceptions are the particular cases of successful application of vibrations to the solution of technological concrete and some simplest theoretical problems. For example, vibration and acoustic methods of the treatment of the bottom-hole zone have already been applied for decades in the oil industry.

Attention should be paid to the fact that the traditional vibration techniques, which are mainly based on the investigations of the dynamics of vibration machines as solid bodies, generally without taking into account the properties of work medium (for example, a multiphase medium), are not worked up enough for the solution of such problems. In addition, ideologically, the hope for success in the application of traditional vibration techniques is related mainly to the fact that the periodical effects on media generate the vibrations (oscillations) in them that can lead (aside from their characteristics) to the intensification of technological processes. Exceptions are the following areas: vibration displacement, classification of granular media, vibration pumps, vibration driving, destruction and crushing of solid bodies, etc. Such formulation (excitation of oscillations in the medium without taking into account the modes of motions that are generated by these oscillations in the work medium), which is considered to be classical in the area of traditional vibration techniques, is not fully applicable to the technological processes of treatment or transportation of multiphase media. Therefore, several proposals to apply traditional approaches, which have established themselves in building, mining, and metallurgy, do not always justify themselves in other industries (for example, in the oil and gas industry, chemical technology, etc.), and sometimes they even lead to inverse results. Therefore, the optimism, which is common at the present time, regarding the application of vibration methods in many sectors of technology is, generally speaking, not scientifically grounded enough and is not always justified. The following example is therein meaningful: in the multiphase media at periodical effects there is either a stable localization of dispersed phases (equilibrium state), or a periodical or translational motion of the phases, or a chaotic motion of a type of homoclinic structures discovered by H. Poincaré; therefore, completely different states (motion or stable equilibriums) take place, although the vibrations are the same. In order to understand such different aspects of waves and oscillations, the development of appropriate a scientific basis is required for multiphase media. Thus, the foregoing enables us to reach a conclusion on the appropriateness of the development of the theory of nonlinear oscillations of multiphase systems that is a scientific basis of wave technology.

The wave technology of multiphase systems in many cases has a quite conditional relation to classical vibrotechnics; it uses other mechanical and mathematical models, formulations of problems, and methods of investigations. As was already mentioned above that the wave processes in multiphase systems can be generated by both external periodical effects and by means of specific properties of the system itself. Vibration machines and devices existing at present are in some cases unusable for the creation of wave technology of multiphase systems. The creation of special types of generators of oscillations and waves, devices, machines, and apparatus on the principles based on the wave and oscillating effects in multiphase systems is reasonable here.

As concerns the ultrasound radiators, their possibilities in technology in some cases are limited by comparatively high energy expenditures. Due to a quick damping of high-frequency oscillations, they cannot always be efficiently applied in large-scale technology processes.

The applied theory of nonlinear oscillations of multiphase systems has basically arisen not only due to the technological processes, but also due to the necessity of dynamic analysis of objects of new techniques, i.e., atomic and common heat-and-power systems [1–8]. For the latest ones, the dynamic analysis of elastic structures, in particular, of pipeline systems interacting with the fluid and gas, is also important. In the establishment of dangerous resonance modes, the determination of boiling crises must be implemented taking into account the oscillating phenomena in multiphase systems. An allied formulation of the problems arises in energetics and the oil-and-gas industry, in particular, during the analysis of dynamics of heat exchange apparatus, and pipeline systems of oil and gas, and petroleum products. Thus, the wave technology of multiphase systems based on the theory of nonlinear oscillations of multiphase systems covers a rather wide range of both the problems of treatment and transportation of multiphase (heterogeneous) media in order to the intensify the technological processes, and the problems related to the growth of reliability and capability of the engineering objects. The following formulation of the problem of nonlinear wave mechanics results from the foregoing.

It is necessary to generate the radical modes of motion (that is, the modes of motion whose velocities exceed the initial motions of media to such extent that efficient technological applications become possible) in multiphase systems due to the nonlinear interactions of oscillations and waves under the conditions of resonances at small energy expenditures. Such formulation of the problem opens another, unconventional view on the theory of oscillations and on its applications in technologies, and, in turn, enables a new promising area of technologies, called wave technologies, to be created.

As examples, we give the following concrete typical formulations:

1. Generation of radical monotone or unidirectional motions of solid and gas inclusions relative to the oscillating fluid.

2. Generation of monotone motions of solid and gas inclusions relative to the oscillating fluid, leading to either their localization in the spatially confined zones of the flow that depend only on the inclusion densities and sizes, or their elimination from these zones.

3. Generation of intensive periodical and nonperiodical (of a kind of chaotic advection or homoclinic structures) motions of inclusions relative to the oscillating fluid that favor the mixing of the multiphase medium, as well as the implementation of certain physicochemical transformations.

4. Generation of stable stagnation regions in the flows near stable equilibrium states, or their elimination by the variation of stability characteristics of the equilibrium states.

5. Generation of radical filtration motions of fluids and gases in the porous wakes saturated by them relative to the oscillating skeleton; generation of powerful additional gradients of pressure, intensifying the filtration processes.

6. Efficient stabilization and suppression of elastic vibrations and shock waves of fluid in pipelines by creating a system of passive suppressors, leading to new principles of reliability.

7. Laminarization and stabilization of the fluid flows in the pipes, channels, and boundary layers by a passive control of boundary layers by various structural elements

and variations in hydrodynamics of the flows, leading to new principles of noiselessness, as well as to new opportunities of implementing the processes of separation of multiphase systems.

8. Generation of cavitational regions in the wave fields, in which the processes of dispersion, mixing, and intensive generation of waves can be implemented for the application in technologies.

Here, many different variants of the formulations of problems are possible. Only several typical formulations are cited in the simplest way.

Therefore, nonlinear wave mechanics is a scientific basis for wave technologies. In turn, the implementation of a number of new applied scientific investigations becomes necessary in some cases during the development of new technologies with respect to concrete technical industries. Nonlinear wave mechanics and wave technologies complement each other. This results in the appearance of new scientific formulations in the field of nonlinear wave mechanics. Therefore, in several cases, the statement of the results of investigations in the field of nonlinear wave mechanics is combined with the description of the application of wave technologies. This enables the perspectives of nonlinear wave mechanics, as well as the validity and perspectives of wave technologies, to be represented more clearly.

II. Wave Mechanisms of Motions; Forces of Wave Nature; Modes of Motions; Nonlinear Resonances

Here we briefly mention some typical models and formulations of the problems of nonlinear wave mechanics of multiphase systems, establishment of the forces of wave nature, and possible modes of motions in the considered systems.

A. Solid Particles Suspended in the Inhomogeneous Field of Fluid Flow

The simplest model of the phenomena considered in the theory of nonlinear wave mechanics is the following model. A solid particle is suspended in a fluid performing a certain movement (Fig. 4) [1,9–12]. For example, the fluid can perform oscillations of

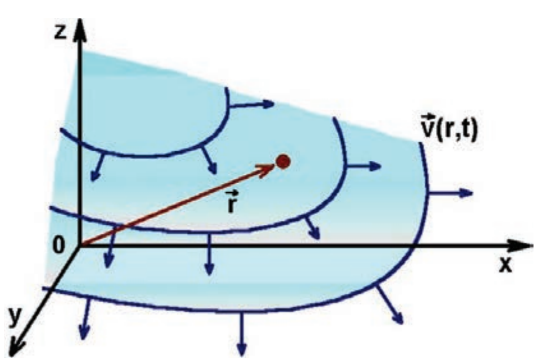

FIG. 4

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